Department I - C Plus Plus

Modern and Lucid C++ for Professional Programmers

Week 9 – Function Templates

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Goals

- **You can explain the difference between Java Generics and C++ Templates**
- **You can implement simple generic functions**
- **You can implement variadic generic functions**
- **You can describe the type concepts required by a function template**

Topics

- **Recap Week 8**
- **Function Templates**
  - Motivation / Introduction
  - Type Concepts
  - Argument Deduction
  - Variadic Templates
  - Gotchas

Recap Week 8

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Why Should we use Algorithms?

- **Correctness**
  - It is much easier to use an algorithm correctly than implementing loops correctly
- **Readability**
  - Applying the correct algorithm expresses your intention much better than a loop
  - Someone else (or even you) will appreciate it when the code is readable and easily understandable
- **Performance**
  - Algorithms might perform better than handwritten loops
    - without sacrificing the "Readability" of your code

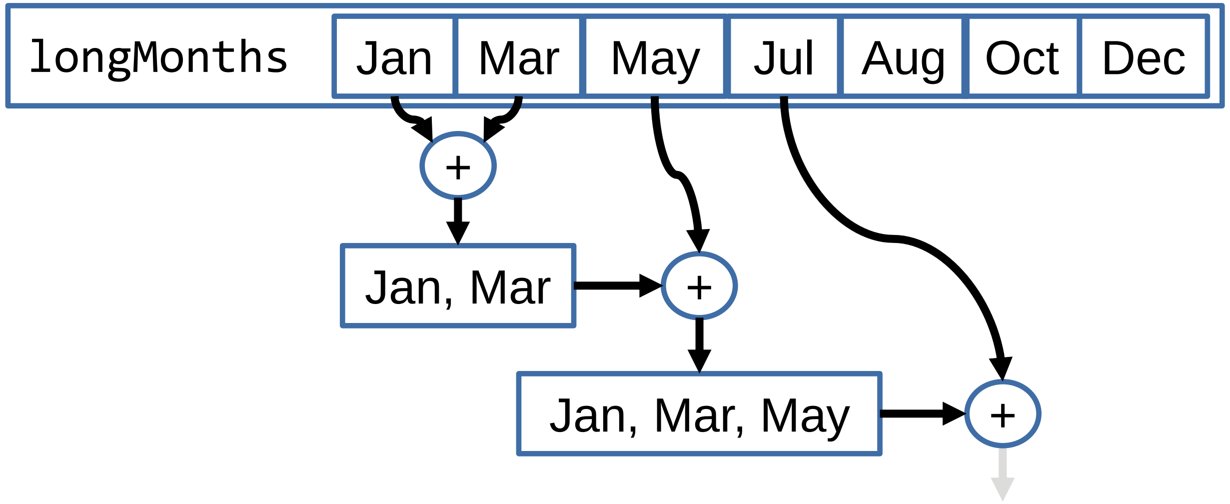
Standard Functor Classes

`#include <functional>`

- **Binary arithmetic and logical**
  - `plus<> (+)`
  - `minus<> (-)`
  - `divides<> (/)`
  - `multiplies<> (*)`
  - `modulus<> (%)`
  - `logical_and<> (&&)`
  - `logical_or<> (||)`
- **unary**
  - `negate<> (-)`
  - `logical_not<> (!)`
- **binary comparison**
  - `less<> (<)`
  - `less_equal<> (<=)`
  - `equal_to<> (==)`
  - `greater_equal<> (>=)`
  - `greater<> (>)`
  - `not_equal_to<> (!=)`

```
transform(v.begin(),v.end(),v.begin(), v.begin(),std::multiplies<>{});
```

- **Some numeric algorithms can be used in non-numeric contexts**
- **Example `std::accumulate`**
  - Sums elements that are addable (+ operator)
  - Or based on a custom binary function
  - Returns the "sum" (accumulated value)



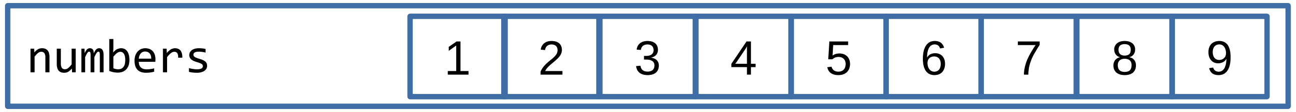

```
std::vector<std::string> longMonths{"Jan", "Mar", "May", "Jul", "Aug", "Oct", "Dec"};
std::string accumulatedString = std::accumulate(
        next(begin(longMonths)), //Second element
        end(longMonths),         //End
        longMonths.at(0),        //First element, usually the neutral element
        [](std::string const & acc, std::string const & element) {
                return acc + ", " + element;
        }); //Jan, Mar, May, Jul, Aug, Oct, Dec
```

Pitfall: Reserving Enough Space

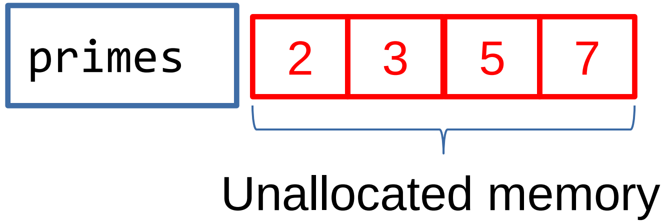
- **If you use an iterator for specifying the output of an algorithm you, need to make sure that enough space is allocated**

```
std::set<unsigned> numbers{1, 2, 3, 4, 5, 6, 7, 8, 9};
std::vector<unsigned> primes{};
auto isPrime = [](unsigned u) {/*...*/};
std::copy_if(begin(numbers), end(numbers), begin(primes), isPrime);
```

- **Vector `primes` is empty, which will not be changed by the iterator passed to `copy`**



- **The output is copied into (possibly) unallocated memory**



Function Templates

Goals:

- You can write your own function templates
- You can determine the concept of a template parameter
- You know the difference between templates and Java generics

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- **Imagine you are tasked with implementing a function that returns the smaller of two given values**
- **For simplification: Just define that function for the fundamental types**

```cpp
auto min(int left, int right) -> int {
  return left < right ? left : right;
}
```

- **Multiple similar implementations just for covering all fundamental types!**
  - What about composite types? `std::string`
  - What about your own types? `Date`, `Word`?
- **Implementing an overload for every possible type leads to code duplication and is not maintainable**
  - Solution: Templates for compile-time polymorphism

```
template <Template-Parameter-List>
FunctionDefinition
```

- **Keyword `template` for declaring a template**
- **Template parameter list: Contains one or more template parameters**
  - A template parameter is a placeholder for a type, which can be used within the template as a type
  - A type template parameter is introduced with the `typename` (or `class`) keyword
- **Example**

Template Parameter

Template Definition

```
template <typename T>
auto min(T left, T right) -> T {
  return left < right ? left : right;
}
```

min.h

```cpp
template <typename T>
T min(T left, T right) {
  return left < right ? left : right;
}
```

smaller.cpp

```cpp
#include "min.h"
#include <iostream>

int main() {
  int first;
  int second;
  if (std::cin >> first >> second) {
    auto const smaller = min(first, second);
    std::cout << "Smaller of " << first
              << " and " << second
              << " is: " << smaller << '\n';
  }
}
```

Template Instantiation

- **The compiler...**
  - ...resolves the function template
  - ...figures out the template argument(s)
  - ...instantiates the template for the arguments (creates code with template parameters replaced)
  - ...checks the types for correct usage

```
template <typename T>
auto min(T left, T right) -> T {
  return left < right ? left : right;
}
```

```
min(first, second)
```

TemplateId

Template Instance

```
min<int>
```

```
auto min(int left, int right) -> int {
  return left < right ? left : right;
}
```

Template Definition

- **Templates are usually defined in a header file**
  - A compiler needs to see the whole template definition to create an instance
  - Function template definitions are implicitly `inline`
- **The definition in a source file is possible, but then it can only be used in that translation unit**
- **Type checking happens twice**
  - When the template is defined: Only basic checks are performed: syntax and resolution of names that are independent of the template parameters
  - When the template is instantiated (used): The compiler checks whether the template arguments can be used as required by the template

- **Generics in Java require bounds defined by interfaces or types**

```
public static <T extends Comparable<? super T>> T min(T first, T second) {
  return first.compareTo(second) < 0 ? first : second;
}
```

  - Only the capabilities specified by those bounds can be used
  - Type erasure removes the argument's type. It can only be instantiated via reflection.

- **C++ Templates use duck-typing**

```
template <typename T>
auto min(T left, T right) -> T {
  return left < right ? left : right;
}
```

  - Every type can be used as argument as long as it supports the used operations
  - The actual type can still be used within a template, e.g. create an instance directly

- **Concept: The requirements a type must fulfill to be useable as an argument for a specific template parameter**
- **What are the requirements of the type `T` in our `min` function template?**

```
template <typename T>
auto min(T left, T right) -> T {
  return left < right ? left : right;
}
```

  - < Comparable with itself: `bool operator<(T, T)`
  - Copy/Move-Constructible, to return T by value
- **In C++20 it is possible to explicitly specify concepts**
  - Allows better checking of template definition (are all requirements fulfilled)
  - Better (easier to read) error messages for failed template instantiations

?

```
template<class InputIt1, class InputIt2, class T>
auto inner_product(InputIt1 first1, InputIt1 last1, InputIt2 first2, T init) -> T {
    while (first1 != last1) {
         init = init + *first1 * *first2;
         ++first1;
         ++first2;
    }
    return init;
}
```

- **`InputIt1/InputIt2`:**
  - `*` (Dereferenceable)
  - `++` (Prefix increment)
  - Only `InputIt1`:
    `!=` with itself
    Result convertible to bool
- **`init + *first1 * *first2`:**
  - `*` on `*first1` and `*first2`
  - `+` on `T` and result of above
- **`T`:**
  - Assignable from result of `init + *first1 * *first2`
  - Copy/Move Constructible

- **The compiler will try to figure out the function template's arguments from the call**

```
template <typename T>
auto min(T left, T right) -> T {
  //Implementation
}
```

```
min(1, 2);
```

Argument 1 has type `int`
Argument 2 has type `int`
Parameter 1 is T
Parameter 2 is T
T becomes `int`

- **Pattern matching on the function parameter list is used for deducing the correct argument**

```
template <typename T>
T min(std::vector<T> const & values) {
 //Implementation
}
```

```
std::vector<double> values{1.0, 2.0};
min(values);
```

Argument has type `std::vector<double>`
Parameter is `std::vector<T> const &`
T becomes `double`

Ambiguities in Deduction

```
template <typename T>
auto min(T left, T right) -> T {
  return left < right ? left : right;
}
```

```
min(1, 1.0)
```

?

```
auto min(int left, int right) -> int {
  return left < right ? left : right;
}
```

```
auto min(double left, double right) {
  return left < right ? left : right;
}
```

- **In specific cases the number of template parameters might not be fix/known upfront**
  - Thus the template shall take an arbitrary number of parameters
- **Example:**

```
template<typename First, typename...Types>
auto printAll(First const & first, Types const &...rest) -> void {
  std::cout << first;
  if (sizeof...(Types)) {
    std::cout << ", ";
  }
  printAll(rest...);
}
```

- **Syntax (ellipses everywhere): `...`**
  - `...` in template parameter list for an arbitrary number of template parameters (Template Parameter Pack)
  - `...` in function parameter list for an arbitrary number of function arguments (Function Parameter Pack)
  - `...` after `sizeof` to access the number of elements in template parameter pack
  - `...` in the variadic template implementation after a pattern (Pack Expansion)

- **Template declaration:**

```
template<typename First, typename...Types>
auto printAll(First const & first, Types const &...rest) -> void;
```

- **Implicit instantiation:**

```
int i{42}; double d{1.25}; std::string book{"Lucid C++"};
printAll(i, d, book);
```

- **Template instance:**

```
void printAll(int const & first, double const & __rest0,
                                 std::string const & __rest1) {
  std::cout << first;
  if (2) { //sizeof...(Types) - Number of arguments in the pack
    std::cout << ", ";
  }
  printAll(__rest0, __rest1); //rest... expansion
}
```

- `sizeof...(<PACK>)` **will be replaced by the number of arguments in the pack parameter**
  - `0, 1, 2, ...`

Pack Expansion of `printAll(rest...);`

```
template<typename First, typename...Types>
auto printAll(First const & first, Types const &...rest) -> void {
 //...
 printAll(rest...);
}
```

- **Pattern: `rest`**
- **The pattern must contain at least one pack parameter**
- **An expansion is a coma-separated list of instances of the pattern**
- **For each argument in that pack an instance of the pattern is created**
- **In an instance of the pattern the parameter pack name is replaced by an argument of the pack**

```
auto printAll(int const & first, double const & __rest0, std::string const & __rest1) -> void {
  //...
  printAll(__rest0, __rest1); //rest...
}
```

- **For the call `printAll(__rest0, __rest1)`: `printAll<double, std::string>`**

```
auto printAll(double const & first, std::string const & __rest0) -> void {
  std::cout << first;
  if (1) { //sizeof...(Types) – Number of arguments in the pack
    std::cout << ", ";
  }
  printAll(__rest0); //rest... expansion
}
```

- **For the call `printAll(<rest0>)`: `printAll<std::string>`**

```
auto printAll(std::string const & first) -> void {
  std::cout << first;
  if (0) { //sizeof...(Types) – Number of arguments in the pack
    std::cout << ", ";
  }
  printAll(); //rest... expansion
}
```

- **What about `printAll()`?**

Base Case

- **What about `printAll()`?**
  - The variadic template `printAll` is not viable, as it requires at least one parameter
- **We need a base case for the recursion**

```
auto printAll() -> void {
}
```

- **Wouldn't it be feasible to just rearange the code in the variadic template?**

```
template<typename First, typename...Types>
auto printAll(First const & first, Types const &...rest) -> void {
  std::cout << first;
  if (sizeof...(Types)) {
    std::cout << ", ";
    printAll(rest...);
  }
}
```

?

Right or Wrong?

?

```
template <typename F, typename...T>
F min(F const & first, T const &...rest) {
  auto const & restMin = min(rest...);
  return first < restMin ? first : restMin;
}

int main() {
  std::cout << min(3, 1, 4, 1, 5);
}
```

Incorrect

The recursive min function template lacks a base case. The call `min()` will not be resolvable. Furthermore, it would be difficult to specify that overload, because it would need to return a value that is smaller than every other value of the given type.
Solution: overload `min(F const & first)`

```
template <typename F, typename...T>
F min(F const & first, T const &...rest) {
  auto const & restMin = min(rest...);
  return first < restMin ? first : restMin;
}
```

Correct

Template code that is not used will not be instantiated. Therefore, the missing overload `min()` will not be recognized.

- **String literals as arguments**

```
auto main() -> int {
  std::cout << min("Gregor Clegane", "Tyrion Lannister");
}
```

- **Possible output:** `Tyrion Lannister`

```
template <typename T>
auto min(T left, T right) -> T {
  return left < right ? left : right;
}
```

`min<char const *>`

```
char const * min(char const * left,
                 char const * right) {
  return left < right ? left : right;
}
```

- **Comparison happens based on the pointer (address) of the arguments**

- **Multiple function templates with the same name can exist**
  - As long as they can be distinguished by their parameter list
- **An overload for pointers is possible**

```
template <typename T>
auto min(T left, T right) -> T {
  return left < right ? left : right;
}

template <typename T>
auto * min(T * left, T * right) -> T {
  return *left < *right ? left : right;
}
```

```
template <typename T>
auto min(T left, T right) -> T {
  return left < right ? left : right;
}

template <typename T>
auto min(T * left, T * right) -> T * {
  return *left < *right ? left : right;
}
```

- **Will this help for the string literal example?**

```
std::cout << min("Gregor Clegane", "Tyrion Lannister");
```

- **And this?**

```
std::cout << min("Samwell Tarly", "Sansa Stark");
```

- **Function templates and "normal" functions with the same name can coexist**

```
template <typename T>
auto min(T left, T right) -> T {
  return left < right ? left : right;
}

template <typename T>
auto * min(T * left, T * right) -> T * {
  return *left < *right ? left : right;
}

auto min(char const * left, char const * right) -> char const * {
  return std::string{left} < std::string{right} ? left : right;
}
```

- **Operators and member functions can be templates too**
- **Example**

```
auto const printer = [&out](auto const & e) {
  out << "Element: " << e;
};
```

```
struct __PrinterLambda {
  template <typename T>
  auto operator()(T const & e) const -> void {
    __out << "Element: " << e;
  }
  std::ostream & __out;
};
```

- **Beware: Don't make operator templates too eagerly, you might end up with unexpected (better) matches for other calls.**

- **Literals and references**

```
template <typename T>
auto min(T const & left, T const & right) -> T const & {
  return left < right ? left : right;
}
```

```
std::cout << min("C++", "Java");
```

```
error: no matching function for call to 'min(const char
[4], const char [5])'
```

- **Literal suffix helps**

```
using namespace std::string_literals;
std::cout << min("C++"s, "Java"s);
```

- **Templates might be a better match**
  - For example because of constness

```
template <typename T>
auto min(T & left, T & right) -> T {
  return left < right ? left : right;
}

auto min(std::string const & left, std::string const & right) -> std::string {
  return std::ranges::lexicographical_compare(left, right, [](char l, char r) {
    return tolower(l) < tolower(r);
  }) ? left : right;
}
```

```
std::string small{"aa"};
std::string capital{"ZZ"};
std::cout << min(small, capital) << '\n'; //ZZ
```

- **Temporary might become invalid**

```
template <typename T>
auto const & min(T const & left, T const & right) -> T {
  return left < right ? left : right;
}
```

```
std::string const & smaller = min("a"s, "b"s);
std::cout << "smaller is: " << smaller;
```

- **Lifetime of temporaries ends at ;**
- **`const &` can extend the lifetime of a temporary, but only if it is a temporary value as a result of the outermost expression**

Right or Wrong?

?

```cpp
template <typename T>
auto min(T const & left, T const & right) -> T const & {
  return left < right ? left : right;
}

auto main() -> int {
  std::cout << min("Java", "Rust");
}
```

Incorrect

This code actually compiles, as both string literals have type `char const[5]`. However, the comparison will still happen on the effective addresses of the arrays.

```cpp
template <typename T>
auto min(T const & left, T const & right) -> T const & {
  return left < right ? left : right;
}

auto main() -> int {
  std::string java{"Java"};
  std::string const rust{"Rust"};
  std::cout << min(java, rust);
}
```

Correct

Even though one string is const and the other is not, the non-const string can be passed as an argument to a const reference.

Summary

- Function templates provide way to specify a set of functions for types that behave in a certain way
- Arguments for a function template instance might be deduced by the compiler
- Variadic templates take an arbitrary number of arguments
- Template instantiation happens at compile-time